DROPWISE EVAPORATIVE COOLING IN RADIATIVE FIELD

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ABSTRACT

This paper investigates the evaporative cooling of solid surfaces induced by the impingement of single water droplets. The solid surface is heated by radiant panels from above; therefore, the radiant heat absorbed directly by the evaporating droplet has to be considered. A theoretical model is presented, which calculates the droplet evaporation time and the solid surface cooling for materials with thermal conductivity spanning over more than two orders of magnitude. In particular, results concerning droplet evaporation on Macor (low thermal conductivity material) are reported and discussed. The model accurately predicts the total evaporation time. It is further validated with transient surface temperature measurements obtained by infrared thermography. The predictions are in excellent agreement with the experimental data. The interfacial heat flux distribution under the evaporating droplet is studied. These single droplet results are currently being used to study the cooling strategies for different materials, and constitute the basis for the formulation of a multi-droplet comprehensive model.

1. INTRODUCTION

The study of the evaporation of a liquid droplet on a hot solid surface is a subject of practical interest in many industrial applications, such as spray cooling of metals in steel industries, vaporization process in internal combustion engines, cooling of turbine blades, and many others. The solid and liquid thermal behavior, the heat transfer phenomena and the relevant parameters governing the evaporative transient constitute the main objectives of the studies conducted in this field.

It is generally recognized that droplet evaporation can be classified into three categories, which depend on the degree of superheat of the solid surface (with respect to the liquid saturation temperature). Therefore, different approaches can be used to study the evaporative transient under conditions of low, intermediate and high superheat respectively. In the regimes of intermediate and high superheat, nucleate or film boiling are the dominant heat transfer modes. A large number of experimental and theoretical investigations have been carried out for liquid droplets deposited on a very high temperature solid surface and, in general, it could be said that a higher number of papers have been published about the regimes of high rather than low superheat. Baumeister & Simon (1973) studied the Leidenfrost transition for liquids as water and liquid metals. More recently, many other contributions on the Leidenfrost evaporation were provided (e.g., Sadhal and Plesset 1979, Avedisian & Koplik 1987). Multi-droplet systems have been investigated by Toda (1972) and by Bonacina *et al.* (1979). These works showed that conduction in the liquid is the relevant heat transfer mode in absence of nucleate boiling. Rizza (1981) provided another numerical investigation for spray evaporation on a hot surface. A two-dimensional transient conduction equation was solved for the solid alone with an arbitrary surface temperature as the boundary condition. Grissom & Wierum (1981) further developed these concepts to define a range of conditions for spray evaporative cooling. Rizza's main assumption of uniform and constant solid-liquid interfacial temperature had already been made by Seki *et al.* (1978), and it was supported by the extensive experimental observations of Makino & Michiyoshi (1978, 1984, 1987). Makino & Michiyoshi (1984) provided a full range of the boiling curve associated with the evaporation of a water drop on a heated surface. Zhang & Yang (1982) observed the interfacial flow patterns of evaporating droplets and discussed the stability of different flow structures at the liquid and air interface. They pointed out that, in steady conditions, the droplet is shaped as a spherical segment with a very smooth surface. This is a basic assumption that will be used in the present study.

A simple model for a single droplet evaporation was proposed by diMarzo and Evans (1987, 1989). This model was limited to evaporation at the liquid-vapor interface in complete suppression of nucleate boiling. Photographic inspection of evaporating droplets (diMarzo & Evans 1987) confirmed that the droplet shape can be approximated by a segment of a sphere.

Most of the above mentioned studies focused on water droplets deposited on high thermal conductivity materials. In that case, the assumption of uniform and constant solid-liquid interfacial temperature is reasonable and the modeling of the liquid region can be de-coupled from the treatment of the solid. This is not the case for dropwise evaporative

cooling taking place on low thermal conductivity materials. Abu-Zaid & Atreya (1989) measured the interfacial temperature at various locations and confirmed that the temperature changes during the transient.
DiMarzo *et al.* (1989, 1992) reported a series of experiments on droplet evaporation on a relatively low temperature solid surface. These studies provided a large amount of data for single water droplets evaporating on solid surface with thermal conductivities ranging from aluminum to Macor, a glass-like material. Many observations, including the evaporation time, the surface temperature distribution and the spatial and temporal behavior of the heat flux on the surface, were given.
The objective of this paper is to provide a basis for the modeling of the cooling effect due to droplet evaporation under radiant input conditions. Extending the range of analysis of a previous model by the same authors, a computer code which describes the coupled thermal behavior of solid and liquid during the evaporative transient is formulated. The predictions of the model are presented and compared with the experimental results. Further analysis of numerical and experimental results is carried out to provide more insight into the evaporative cooling mechanism.

2. PHENOMENOLOGY

Some detailed descriptions of the droplet evaporation phenomenology and of the solid surface temperature behavior were provided by diMarzo and Evans (1987, 1989) and by Klassen *et al.* (1990). Experiments were conducted on aluminum (k = 180 W/m·C) and on Macor (k = 1.3 W/m·C). The thermal conductivity more than the thermal diffusivity of the materials is the main parameter characterizing the evaporative cooling behavior.
In the previous works by diMarzo & Evans (1987, 1989) and by Klassen *et al.* (1990), the operative conditions were those of a single droplet gently deposited on a solid surface heated by conduction from below. All these experiments showed that the wetted area can be considered as constant for the entire evaporative transient. Experiments conducted by Kidder (1990) and by diMarzo *et al.* (1992) showed that the same assumption is not realistic when the solid surface is heated by radiation from above, since the droplet visibly shrinks, in this case, during the transient. This phenomenon had been early observed and studied by several researchers (Adam & Jessop 1925, Herzberg & Marian 1970, Simon & Hsu 1971). They showed that, when a liquid droplet impinges a hot solid surface, the solid-liquid contact angle is characterized by a critical value, dependent on the physical properties of both materials. Below this critical value, called receding angle, the droplet contact area cannot remain constant and it starts to shrink. Since the shape of a droplet gently deposited on a solid surface has been shown to be that of a segment of sphere, the receding angle results to be related to the shape parameter β, defined as $\beta = R/R_{sph}$, where R is the radius of the wetted area and R_{sph} is the radius of the spherical droplet of equal volume.
When the droplet impinges the solid surface and the evaporative transient begins, the initial value of the shape parameter, β_0, is directly observed. When heat is supplied by radiation from above, the amount of heat absorbed directly by the water upper layer causes the droplet to spread out under the effect of decreasing surface tension. This difference in the initial droplet shape is confirmed by the experiments conducted by Klassen *et al.* (1990) and by Kidder (1990) on Macor heated by conduction from below and by radiation from above respectively. Figure 1 shows the behavior of the initial value of the shape parameter, β_0, under both conductive and radiative heat input conditions for the same values of the initial solid surface temperature.

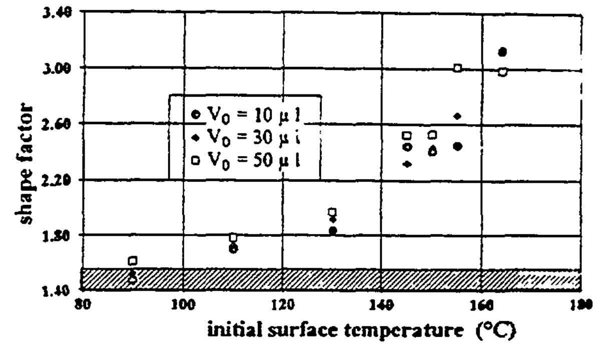

Fig. 1 Shape factor (β_0) versus initial surface temperature for Macor. Shaded area = solid surface heated by conduction; o, ◇, □ = solid surface heated by radiation.

3. THEORETICAL MODEL

3.1 Previous Work

The original model by diMarzo *et al.* (1987, 1989) was used to gain insight into the evaporative process mechanism in the special case of droplets laid on solid surfaces heated by conduction from below. The evaporative cooling behavior for different conductivity materials (spanning over more than two orders of magnitude, from Macor to aluminum) was analyzed for an identical heat sink. As a result of these studies, it was found that a constant and uniform interfacial temperature can be assumed for high conductivity materials and leads to meaningless results for a low thermal conductivity solid (Tartarini & diMarzo 1991). The conductive version of the model by diMarzo *et al.* (1987, 1989) was also used to investigate the interfacial temperatures and heat fluxes under the droplet, where direct measurements are unavailable. An important result of previous analyses consisted in observing that the heat flux is not uniform nor constant during the evaporative process. The spatial distribution also indicated that most of the evaporation takes place at the outer edge of the droplet.
Some basic assumptions are made in the model formulation:

- Heat conduction is assumed to be the only heat transfer mechanism in the liquid droplet and in the solid. Nucleate or film boiling are not present.
- The wetted area on the solid surface covered by the

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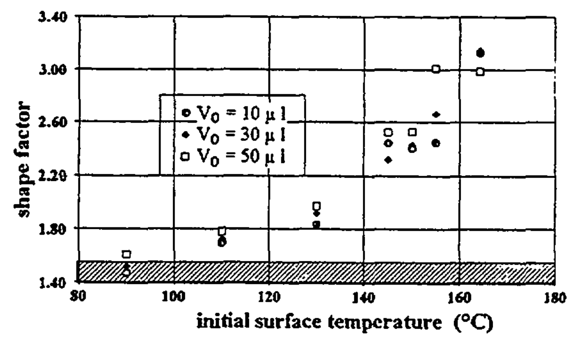

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Some basic assumptions are made in the model formulation:

- Heat conduction is assumed to be the only heat transfer mechanism in the liquid droplet and in the solid. Nucleate or film boiling are not present.
- The wetted area on the solid surface covered by the

droplet remains constant for contact angles greater than the value of the receding angle, regardless of droplet volume decreasing.

- The model generating the transient droplet shape also assumes that, at the receding angle, the droplet has reached a spherical cap configuration. This is reasonable because, in order for the surface tension to shrink the wetted surface, the liquid-vapor surface configuration must maximize the bounded volume. This receding angle configuration identifies the aspect ratio of the droplet which will be preserved for all the remaining portion of the transient. Chandra and Avedisian (1991) showed that, for an evaporating droplet, this angle is less than 90°.

3.2 The Experimental Apparatus

The radiant heat input is provided by two panels mounted above the surface of a Macor square tile (0.1524 x 0.1524 x 0.0254 m). The panels can reach temperatures in excess of 800°C and can be approximated to black bodies. They are conical in shape with an external diameter of about 0.2 meters. These two panels are positioned above the Macor tile, on two opposite sides of the tile with their axis at 30° from the vertical and facing the tile surface. The panels are fed by a three-phase power supply which is controlled on a temperature feedback, and are held at a constant temperature set point. The Macor tile is pasted onto a chilled plate which is kept at near ambient temperature by a water flow. The radiant boundary condition as well as the thermal condition at the lower surface of the tile are designed to obtain a linear temperature profile in the tile depth and to insure that the tile exposed surface is isothermal over the droplet impingement region, prior to the initiation of the transient. The Macor tile transient surface temperature distribution is recorded by an infrared camera. The infrared image is correlated to a temperature distribution. The 256 shades of gray are related to a temperature scale of about 120°C. The scale is set by simultaneously measuring the temperature of a given surface point with a thermocouple probe and via the infrared camera reading. The spacial resolution is about 10 pixel/mm and the temperature resolution is 2°C/gray-shade which yields an accuracy of about ±1°C. The transient temperature distribution is recorded on a VCR and selected frames during the transient are grabbed by a PC to be analyzed.

3.3 Model Formulation

The modeling of the coupled solid and liquid thermal behavior is described by the transient conduction equation for both domains with the appropriate boundary conditions:

$$\textit{solid domain}: \quad \frac{\partial T}{\partial t} = \kappa_s \nabla^2 T - H_{\mu,z}\big|_{z=0} \qquad (1)$$

$$\textit{liquid domain}: \quad \frac{\partial T}{\partial t} = \kappa_l \nabla^2 T - H_{\mu,z} \qquad (2)$$

Assuming that both diffusion and reflection at the bottom of the droplet are negligible, one can write the volumetric heat generation in the liquid layer as:

$$\frac{\partial F}{\partial z} = H_{\mu,z} = \int_0^{\infty} E_\lambda \alpha_\lambda \times \times \int_0^{\pi/2} \frac{2}{\mu} \Phi_{\lambda,\theta} \sin\theta \cos\theta \, e^{-\frac{\alpha_\lambda z}{\mu}} \left(1-\rho_{\lambda,\theta}\right) d\lambda \, d\theta \qquad (3)$$

The absorption coefficient α is a very strong function of the wave length λ (Siegel & Howell 1981), the direction cosine μ is given by the Snell's law, the fractional surface area coverage Φ depends on the geometrical configuration of the radiant heat source, and the reflectivity ρ is less than 0.1 for θ less than 65 and it is given by the electromagnetic theory. For the typical experimental conditions (Kidder 1990, diMarzo *et al.* 1992), the panels temperature is less than 750°C. The direct radiation contribution is maximum at the liquid-vapor interface; however, the contribution of the radiant heat input in the layer thickness is not negligible, and the model takes it into account for each value of the axial coordinate z.

By introducing an overall heat transfer coefficient h at the exposed solid surface, the boundary conditions at the liquid-vapor interface can be written as:

$$-k_l \nabla T + q_{top} = h(T_i - T_a) + 0.624\, h_c \left(\frac{D}{\kappa_a}\right)^{\frac{2}{3}} \frac{\Lambda}{c_a} \frac{x_i - x_a}{1 - x_a} \qquad (4)$$

where q_{top} denotes the radiant heat flux that is absorbed by the top layer of the liquid.

The set of boundary conditions at the liquid-solid interface and at the exposed solid surface can be written as follows:

$$at \;\; 0 \le r \le R,\; z=0: \quad T = T_0 \; ; \; k_s \frac{\partial T}{\partial z} = k_l \frac{\partial T}{\partial z} + q_{z=0} \qquad (5)$$

$$at \;\; r > R,\; z=0: \quad k_s \frac{\partial T}{\partial z} = h(T_{s,0} - T_a) + \varepsilon_s \sigma (T_s^4 - T_a^4) \qquad (6)$$

In order to evaluate the amount of radiant heat that is directly absorbed by the droplet and the percentage that reaches the solid-liquid interface, experimental tests and numerical simulations have been carried out.

The heat flux incident on the water droplet surface, q_{inc}, was measured (Kidder 1990) with a radiometer at various heaters temperatures. It was found that the heat flux on the surface was about 18% of the flux produced by the heaters, that is:

$$q_{inc} = 0.18\, \varepsilon\, \sigma\, T_H^4 \qquad (7)$$

In the numerical code, the conical heaters have been simulated as a series of separate rectangular shaped panels, each at a different angle to the droplet (Kidder 1990).

Since the heaters surface area, the total absorption coefficient, the incident heat flux and the droplet surface area are all known, Eq. (3) allows one to calculate the amount of incident energy (from the i-th rectangular heater element) that is absorbed by each mesh of the droplet. This is possible because the coordinates of each mesh are known step by step, and Eq. (3) can be applied as if every mesh consisted of a disk of known thickness and position inside

the whole droplet.
Also under radiant heat input conditions, as well as in the conductive case (see Tartarini *et al.* 1990), extremely strong local thermal gradients at the drop initial contact preclude the solution of this problem with conventional finite difference schemes. The solution is obtained by using a Boundary Element Method (BEM) for the solid region and a Control Volume Method (CVM) for the liquid region. The BEM is described in detail by Wrobel & Brebbia (1981), while the CVM used here is described by Tartarini *et al.* (1990). Although the droplet and the solid are treated separately by different numerical methods, the temperatures in the droplet and along the solid surface are solved simultaneously at each time step by coupling the CVM and the BEM in the numerical model.

4. RESULTS AND DISCUSSION

In the present work, a computer code has been formulated on the basis of the previously described theoretical model. Validation has been obtained by numerous comparisons between numerical predictions and experimental data provided by Kidder (1990) and by diMarzo *et al.* (1992). The droplet evaporation time and the solid surface transient temperature distribution are the main parameters which provide an estimate of the effectiveness of the numerical predictions. The comparison between experimental data and numerical prediction for the total evaporation time is presented in Fig. 2.

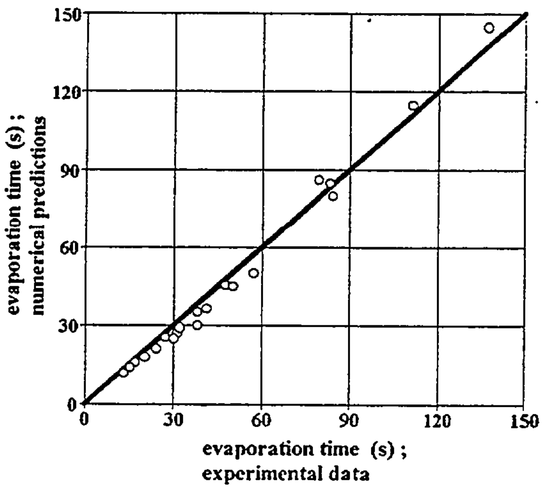

Fig. 2 Model validation: total evaporation time for droplets with V_0 = 10, 30 and 50 µl on Macor; comparison between experimental data and numerical predictions.

In this figure, data and numerical results concerning droplets of 10, 30 and 50 µl are reported. The experiments were conducted with the initial surface temperature of the Macor tile ranging from 90·C to 165·C. The agreement between data and numerical predictions is generally within 5%. Some discrepancies were observed for evaporation times greater than 160 s (low surface temperatures and big initial volumes) and for high surface temperatures (some experiments were also carried out with T_s= 180·C). Both these conditions, however, are in conflict with the initial assumptions of the present work: in fact, very low evaporation times coincide with the onset of convective motion inside the droplet, while Macor temperatures over 160·C induce nucleate boiling.
In Fig. 3 and Fig. 4, experimental and numerical surface temperature curves are reported. They show four reference cases of surface temperature distribution after 30% and 90% of the total evaporation time respectively. Initial droplet volumes of 10 and 30 µl, subjected to initial surface temperatures of 110, 130 and 145 ·C, are considered here, and in all cases a very satisfactory accuracy of the numerical simulation is observed. This is consistent with the results (Tartarini & diMarzo 1990) which had been provided by the previous code version for solid surfaces heated by conduction from below.

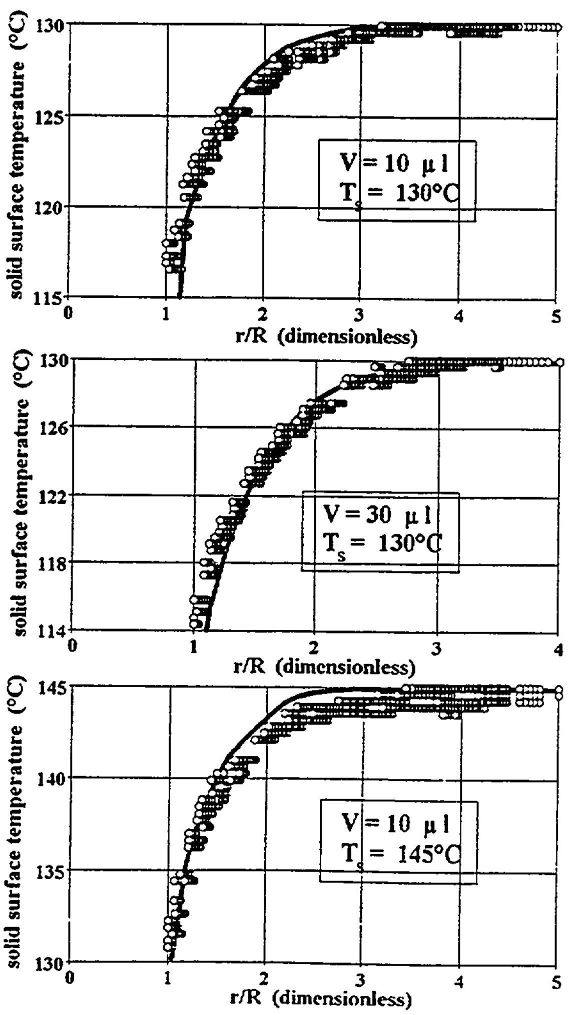

Fig. 3 Model validation: solid surface temperatures for water on Macor at t = 0.3 τ. Solid line = numerical simulation; O = experimental data.

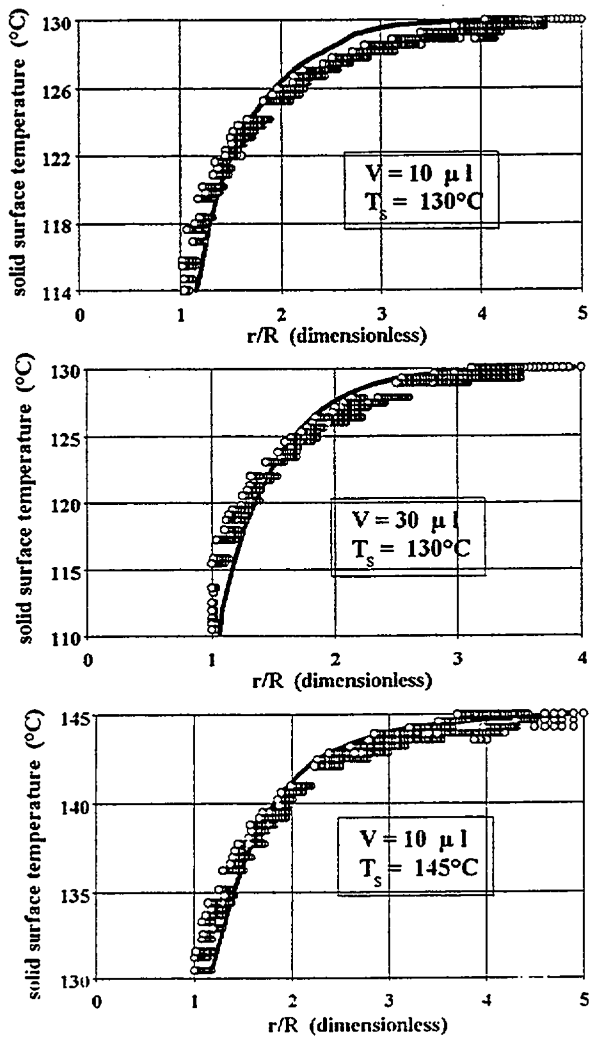

Fig. 4 Model validation: solid surface temperatures for water on Macor at t = 0.9 τ. Solid line = numerical simulation; O = experimental data.

The code accuracy in both situations is remarkable if one considers the very different behavior of the droplets in terms of initial and transient values of the wetted area for conductive and radiative heating of the solid surface.
A useful information that is provided by the code, and that is needed for the multi-droplet extension of the model, consists of the calculation of the solid-liquid interfacial heat flux during the evaporative transient. Two examples of the interfacial heat flux behavior are reported in Fig. 5, which also confirms that the interfacial heat flux between water and low conductivity materials like Macor is not constant nor uniform during the evaporative transient.
These observations provide some insight on the cooling strategies to be used for different materials, and constitute the basis for the formulation of a multi-droplet comprehensive model.

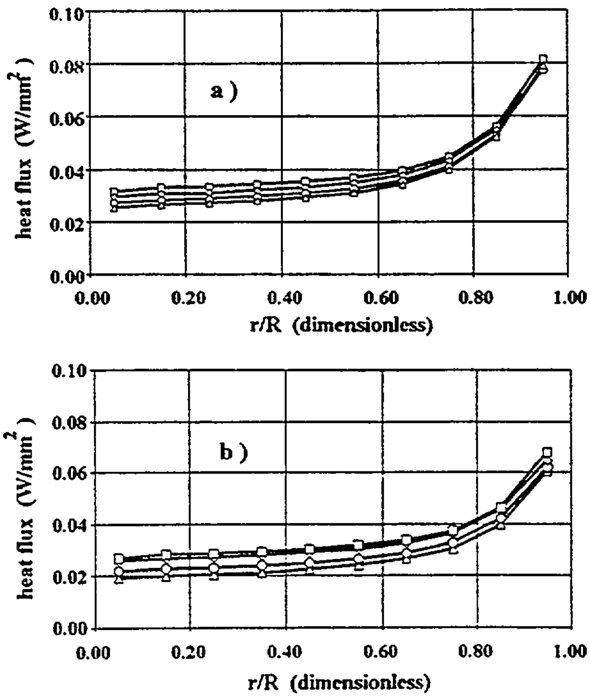

Fig. 5 Liquid-solid interfacial fluxes for water droplets with T_s = 130°C on Macor;
a) V = 10 μl - t=0.3 τ (▵); t=0.5 τ (O); t=0.7 τ (◊) and t=0.9 τ (□);
b) V = 30 μl - t=0.3 τ (▵); t=0.5 τ (O); t=0.7 τ (◊) and t=0.9 τ (□).

5. CONCLUSIONS

The cooling effect due to the evaporation of a liquid droplet on a hot solid surface heated by radiation from above has been investigated. The theory for the formulation of a model for the prediction of the thermal behavior of the droplet-solid interaction has been reviewed. On the basis of a large number of experimental results, the model has been presented and validated over various parameters. Model predictions for a variety of conditions are used to gain insight into the evaporative process mechanism.
The new model, now including both conductive and radiative heat input options, constitutes a validated instrument to analyze the single-droplet evaporative cooling for a wide range of materials. Its extension to multi-droplet systems (sprays) is currently in progress.

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NOMENCLATURE

c	specific heat
D	air-steam mass diffusivity
E_λ	spectral radiative flux
F	total radiative flux
H	radiative heating rate
h	overall heat transfer coefficient
h_c	convective heat transfer coefficient
k	thermal conductivity
q	heat flux
r	radial coordinate
R	radius of the wetted area
t	time
T	temperature
x	molar fraction of steam in air
z	axial coordinate
Greek letters	
α_λ	spectral absorption coefficient of water
β	shape parameter
ϵ	emissivity
θ	polar angle
κ	thermal diffusivity
Λ	liquid latent heat of vaporization
λ	wavelength
μ	direction cosine
ρ_λ	reflectivity of the air-water interface
σ	Stefan-Boltzmann constant
τ	total evaporation time
Φ	fractional surface area
Subscripts	
a	air
H	heaters
i	interfacial
l	liquid
s	solid
0	initial

REFERENCES

Abu-Zaid, M. & Atreya, A. 1989, Effect of Water on Piloted Ignition of Cellulosic Materials, NIST Rpt., GCR-89-561.

Adam, N. & Jessop, G. 1925, Angles of Contact and Polarity of Solid Surfaces, J. Chem. Soc., vol. 127, pp. 1863-1868.

Avedisian, C.T. & Koplik, J. 1987, Leidenfrost Boiling of Methanol Droplets on Hot Porous/Ceramic Surfaces, Int. J. Heat Mass Transfer, vol. 30, pp. 379-393.

Baumeister, K.J. & Simon, F.F. 1973, Leidenfrost Temperature - Its Correlation for Liquid Metals, Cryogens, Hydrocarbons and Water, ASME J. Heat Transfer, vol. 95, pp. 166-173.

Bonacina, C., Del Giudice, S. & Comini, G. 1979, Dropwise Evaporation, ASME J. Heat Transfer, vol. 101, pp. 441-446.

Chandra, S. & Avedisian, C.T. 1991, On the Collision of a Droplet With a Solid Surface, Proc. of the Royal Society of London, vol. 432, pp. 13-41.

diMarzo, M. & Evans, D.D. 1987, Dropwise Evaporative Cooling of High Thermal Conductivity Materials, Int. J. Heat & Technology, vol. 5 (1-2), pp. 126-136.

diMarzo, M. & Evans, D.D. 1989, Evaporation of a Water Droplet Deposited on a Hot Thermal Conductivity Surface, ASME J. Heat Transfer, vol. 111, pp. 210-213.

diMarzo, M., Kidder, C.H. & Tartarini, P. 1992, Infrared Thermography of Dropwise Evaporative Cooling of a Semiinfinite Solid Subjected to Radiant Heat Input, Int. J. Exp. Heat Transfer, vol. 5, pp. 101-114.

Grissom, W.M. & Wierum, F.A. 1981, Liquid Spray Cooling of a Heated Surface, Int. J. Heat Mass Transfer, vol. 24, pp. 261-271.

Herzberg W.J. & Marian, J.E. 1970, The Receding Contact Angle, J. Colloid Interface Science, vol. 33, pp. 164-171.

Kidder, C. 1990, Dropwise Evaporative Cooling of a Ceramic Solid Surface Heated by Radiation, MS Thesis, University of Maryland, Dept. of Mechanical Engineering.

Klassen, M.S., diMarzo, M. & Sirkis, J. 1990, Infrared Thermography of Dropwise Evaporative Cooling, ASME HTD, vol. 141, pp. 117-121.

Makino, K. & Michiyoshi, I. 1978, Heat Transfer Characteristics of Evaporation of a Liquid Droplet on Heated Surfaces, Int. J. Heat Mass Transfer, vol. 21, pp. 605-613.

Makino, K. & Michiyoshi, I. 1984, The Behavior of a Water Droplet on Heated Surfaces, Int. J. Heat Mass Transfer, vol. 27, pp. 781-791.

Makino, K. & Michiyoshi, I. 1987, Discussion of Transient Heat Transfer to a Water Droplet on Heated Surfaces Under Atmospheric Pressure, Int. J. Heat Mass Transfer, vol. 30, pp. 1895-1905.

Rizza, J.J. 1981, A Numerical Solution to Dropwise Evaporation, ASME J. Heat Transfer, vol. 103, pp. 501-507.

Sadhal, S.S. & Plesset, M.S. 1979, Effect of Solid Properties and Contact Angle in Dropwise Condensation and Evaporation, ASME J. Heat Transfer, vol. 101, pp. 48-54.

Seki, M., Kawamura, H. & Sanokawa, K. 1978, Transient Temperature Profile of a Hot Wall Due to an Impinging Liquid Droplet, ASME J. Heat Transfer, vol.100, pp 167-169.

Siegel, R. & Howell, J.R. 1981, Thermal Radiation Heat Transfer, Hemisphere Publishing Corporation, New York.

Simon, F.F. & Hsu, Y.Y. 1971, Wetting Dynamics of Evaporating Drops on Various Surfaces, NASA Technical Memorandum, NASA TM X-67913.

Tartarini, P. & diMarzo, M. 1990, The Solid-Liquid Interfacial Conditions for Dropwise Evaporative Cooling, Int. J. Heat & Technology, vol. 10 (3-4), pp. 130-144.

Tartarini, P., Liao, Y. & diMarzo, M. 1990, Transient Cooling of a Hot Surface by Droplets Evaporation, UMCP Mechanical Engineering Report, No. 90-6.

Toda, S. 1972, A Study of Mist Cooling. First Report: Investigation of Mist Cooling, Heat Transfer Japanese Research, vol. 1 (3), pp. 39-50.

Wrobel, L.C. & Brebbia, C.A. 1981, A Formulation of the Boundary Element Method for Axisymmetric Transient Heat Transfer Conduction, Int. J. Heat Mass Transfer, vol. 24, pp. 843-850.

Zhang, N. & Yang, W.-J. 1982, Natural Convection in Evaporating Minute Drops, ASME J. Heat Transfer, vol. 104, pp. 656-662.